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Numerical Analysis of Slope Reinforced with Piles: A Case Study of Upper Trishuli 3B Hydroelectric Project

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Abstract
A powerhouse slope of Upper Trishuli 3B Hydroelectric Project is taken as a case study to perform stability analysis of the steep cut slopes by performing numerical analysis on the unstable and pile reinforced soil slope. Samples from top, middle and bottom of the slope were tested in laboratory for soil classification and shear parameters. Numerical models were developed in PLAXIS 2D V20 to study the parametric variation of three parameters of vertical pile i.e. diameter, length and spacing based on factor of safety. A comparative study was performed by changing configuration of vertical pile to combination of cross beam and vertical pile which is called h-type anti-slide pile (hTP pile). The result of the study is that hTP pile have better performance in slope than vertical pile only.

Keywords
Slope stability, Finite Element Method, Pile, Factor of Safety, Parametric variation, h type anti-slide pile

1. Introduction

Nepal, being a mountainous country, natural conditions such as steep topography, unstable geology, severe rainfall, floods and earthquakes exists. Infrastructures such as road, hydropower built in the hills of Nepal are strongly susceptible to slope failure. Slope instability is largely caused by slope morphology, low rock-mass quality, morphological changes generated by nature, man, and hydro-meteorological conditions, all of which modify the regolith soil and rock's shearing resistance[1].

The power house of Upper Trishuli 3B Hydroelectric Project is being constructed at the base of huge hill cut slope. So, there is always a potential risk of slope failure .Various slope failure prevention works have been applied to increase its stability i.e. soil nailing, shot-crete and grid beams.The existing cut slope of powerhouse area is shown in **Figure 1**. In this study, piles as an alternative for slope reinforcement is analyzed on the basis of factor of safety.

The study area is located in Nuwakot and Rasuwa district of Bagmati Province of Nepal between longitudes of 85°10'11" and 85°12'01" and latitudes of 27°15'12" and 28°01'54".The project is located in the Middle Hilly Region's Trishuli River, which is a large network of hills and valleys. The location of powerhouse is shown in **Figure 2**.

Figure 1: Powerhouse cut slope of Upper Trishuli 3B Hydroelectric Project

1.1 Slope stability using piles

A pile is a slender structural member made of steel, concrete or wood. The pile is constructed in-situ by digging a pit and filling it with concrete, or it can be rammed into the ground. The friction of a pile surface produces a resistance force against the driving force of a slope. The pile installed in the slope suffers from

Figure 2: Powerhouse location of Upper Trishuli 3B Hydroelectric Project

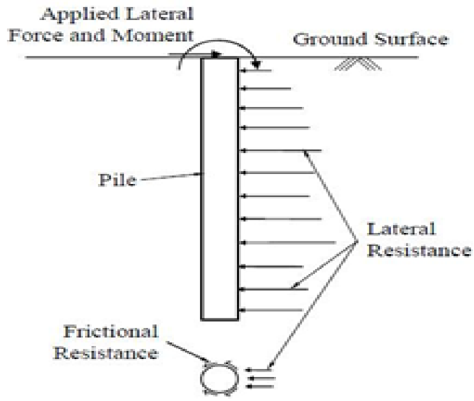

Figure 3: Mechanism of resisting lateral load by pile [3]

lateral force, thus it is called a passive pile [2].

When lateral loads are applied, piles behave like transversely loaded beams. They use the lateral resistance of soil to transmit lateral weight to the surrounding soil mass. When a pile is laterally loaded, a portion or the entire pile attempts to move horizontally in the direction of the applied force, resulting in pile bending, rotation, or translation. The piles presses against soil in-front of it (the soil mass lying in the direction of applied load), generating compressive and shear stresses and strains in the soil that offers resistance to the pile movement[3].**Figure 3** shows the mechanism of resisting lateral load by pile.

When vertical piles are connected with a cross beam, a new type of structure is formed which is called h-type anti-slide pile (hTP pile). **Figure 4** shows the mechanical model of hTP. It resemble small letter h of english alphabet and used to improve slope stability . So, it is called h-type anti-slide pile (hTP pile). It is made up of a back pile, a front pile, and a connecting beam. Each of the three components is rigidly connected to the others. The retaining mechanism of hTP is a combination of pile body, soil mass between the piles and the resistance in front of hTP. All together they increase the pile resistance against the thrust of large landslide[4].

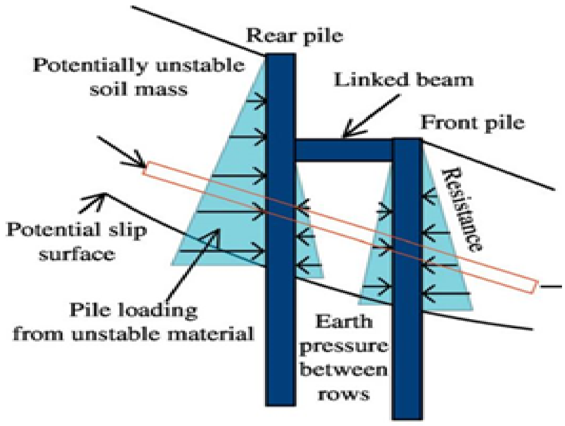

Figure 4: Mechanical model of hTP [4]

1.2 Finite Element Method

This method is more powerful, accurate, reliable and versatile method to find the slope deformation and stress analysis. The soil mass is divided into small-node elements. This method utilizes the stress-strain relationship among the soil elements and helps better visualization of deformation of soil mass and no assumption for location of failure surface is made. This method has been widely accepted for the analysis of slope stability [5]. Strength reduction method, also called $\phi - c$ reduction method is used to obtain the factor of safety of the slope. In this technique, the strength parameters 'tan ϕ' and 'c" of the soil are reduced in steps until the soil mass fails.

1.3 Research Review

Many researchers in the past had performed stability analysis of the slope analytically or by numerical modeling. Numerical modeling was done using different software based on LEM or FEM to find the factor of safety. (Rocscience Inc, 2004) stated that there are three important aspects that influence slope stability analysis i.e. Materials properties of slope model, Factor of Safety (FOS) and Slope failure [6]. (Wanstreet, 2007) performed finite element analysis of earth slopes and concluded that the finite element technique performed admirably in calculating the factor of safety and the failure surface when used in conjunction with the strength reduction method. The factor of safety of a soil slope can be determined using finite element analysis, which is a useful tool for slope failure studies [7]. (Ausilio et al., 2001) performed the slope stability of piled slopes using kinematic approach of limit analysis and concluded that when piles are used in the area between the middle and the bottom of the slope, they appear to be highly efficient [8]. (Surjandari et al., 2017) carried out slope stability analysis of slope reinforced with mini piles. Variation of safety factor with different values of parameters of piles i.e. dimension, depth and spacing of piles was studied and the optimum parameters were identified [2].

1.4 Laboratory Testing

Disturbed but representative soil samples were collected from the top, middle and bottom of the powerhouse slope. The collected samples from the field were brought to Central Material Testing Laboratory (CMTL), IOE, Pulchowk Campus for characterization of soil and find the shear parameters which can be used in material model. The lab tests performed are as follows:

1. Specific Gravity Determination
2. Particle Size Analysis- Sieve Analysis, Wet Analysis
3. Atterberg's Limit- Liquid Limit(LL) and Plastic Limit(PL)
4. Shear parameters(C and ϕ) - Direct Shear Test
5. Permeability test

The details of the laboratory test results are shown in **Table 1**

Table 1: Summary of material properties

Description	Slope		
	Top	Middle	Bottom
Field density (kN/m^3)	16.35	16.7	15.05
Moisture content(%)	17.9	20.8	18.01
Specific Gravity	2.63	2.61	2.68
D_{10}	0.04	0.05	0.6
D_{30}	0.45	7.5	4.6
D_{60}	10	0.15	22
Cu	250	150	36.67
Cc	0.5026	0.06	1.603
Soil Type (USCS)	silty sand	silty sand	well graded gravel
Liquid Limit(%)	22.426	22.59	21.414
Plastic Limit(%)	-	-	-
Cohesion (kN/m^2)	22.9	13.7	17.43
Angle of friction, ϕ	31.27	33.93	32.82
Coefficient of permeability, k (m/day)	0.0359	0.09	0.3504

2. Numerical Modeling

Two dimensional numerical models are developed in PLAXIS 2D V20 for the computation of unreinforced slope as well as slope reinforced with piles. Piles are modeled as combination of elastic plate element and interface elements. Since piles are modeled as plate elements, it is required to input the values of axial stiffness and bending stiffness of the reinforcing element. The calculation of axial stiffness (EA) and bending stiffness (EI) for circular piles are done based on the equations listed below.

$$EA = \frac{E\pi d^2}{4} \quad (1)$$

$$EI = \frac{E\pi d^4}{64} \quad (2)$$

Where, E is modulus of elasticity of pile material and d is the diameter of pile.

Interface components can be used to reenact the interaction between a structure and the earth. The interface springs' elastic shear and normal stiffness are calculated internally using the stiffness parameters of the relevant material set [9].

2.1 Material model

The failure criterion of soil model is assumed as Mohr-Coulomb (elastic-perfectly plastic). Linear elastic model is used for pile. The material model for pile and soils are presented in **Table 2** and **Table 3** respectively.

Table 2: Material model parameters for pile[10]

Parameters	Input value
Material Type	Concrete
Modulus of Elasticity, E(kPa)	25000000
Poisson's ratio, ν	0.16
Unit weight, γ (kN/m^3)	24

Table 3: Material model parameters for soil

Parameters	**Slope**		
	Top	**Middle**	**Bottom**
Cohesion(kPa)	22.9	13.7	17.43
Angle of internal friction, ϕ	31.27	33.934	32.82
Modulus of Elasticity E (kPa)	10000	10000	40000
Poisson's ratio, ν	0.3	0.3	0.3
Unit weight (unsaturated), γ_{unsat}(kN/m^3)	16.37	16.72	17.79
Unit weight (saturated), γ_{sat}(kN/m^3)	20.68	20.05	20.93
Material type	Un-drained	Un-drained	Un-drained
Permeability, k_x, k_y(m/day)	0.03585	0.0898	0.3504

2.2 Geometric Model

The cross section of powerhouse slope of Upper Trishuli 3B hydroelectric project is formulated for numerical analysis. The geometric model is shown in **Figure 5**. The model is assumed as plain strain problem. The model is discretized with medium mesh density on the soil cluster and the meshing is done by 15-nodded triangular element.

2.3 Parametric Variation

Numerical models are computed varying three parameters of vertical piles .i.e. length, diameter and spacing. Length is varied to be 16m, 18m, 20m and 22m. Diameter of pile is varied to be 0.2m, 0.3m, 0.4m, 0.5m, 0.6m, 0.7m, 0.8m and 1m. Spacing is varied to be 4m, 6m, 8m and 10m. 128 numerical models were generated for modeling piled slope with unique combination of parameters.**Figure 6** shows the slope model with vertical pile.

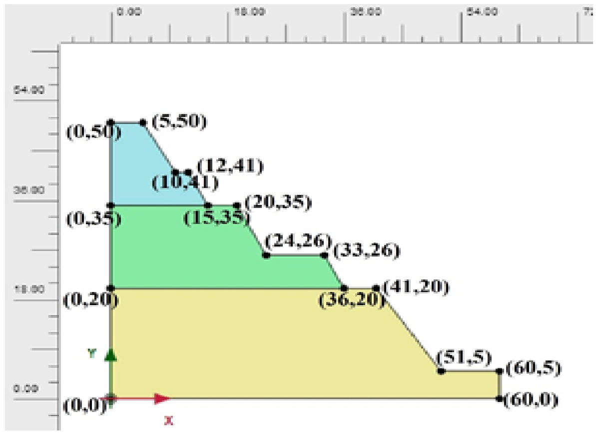

Figure 5: Geometric model of the slope

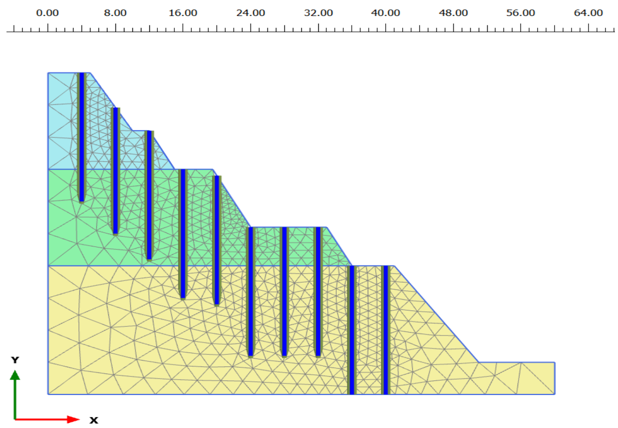

Figure 6: Slope Model with vertical pile

2.4 h type anti-slide (hTP) pile

Numerical models are computed by changing the configuration of vertical piles to the combination of cross beams and vertical piles, which is also called h type anti-side pile. 7 numerical models were generated by installing hTP pile at different location from top to bottom as shown in figures below.

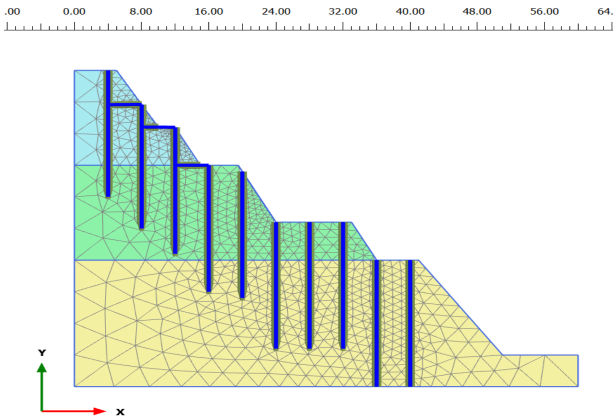

Figure 7: Slope model with hTP pile at top

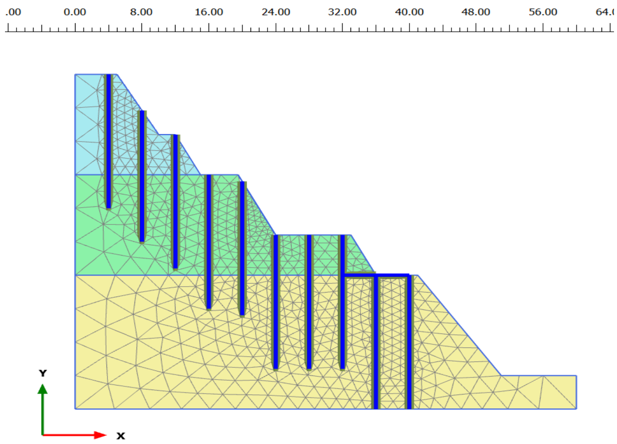

Figure 9: Slope model with hTP pile at bottom

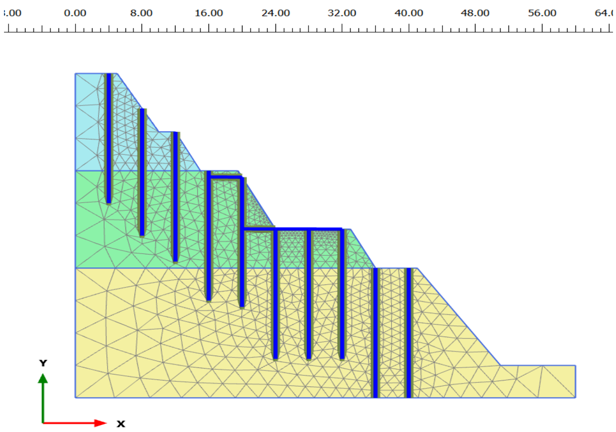

Figure 8: Slope model with hTP pile at middle

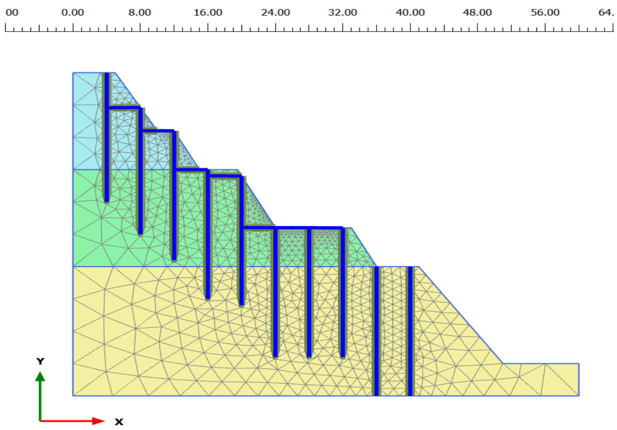

Figure 10: Slope model with hTP pile at top and middle

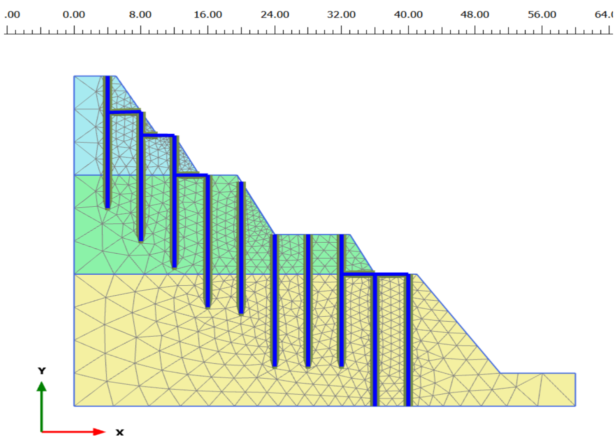

Figure 11: Slope model with hTP pile at top and bottom

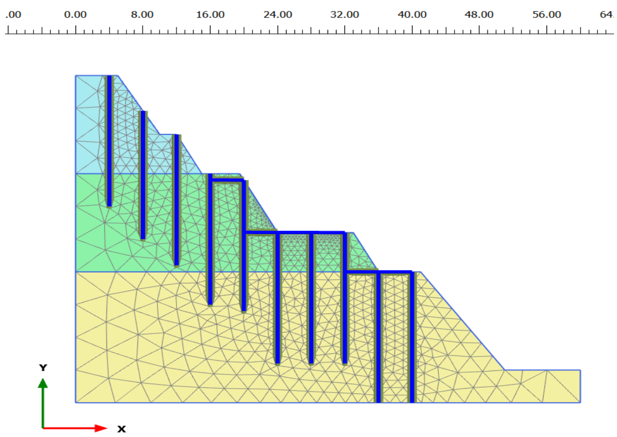

Figure 12: Slope model with hTP pile at middle and bottom

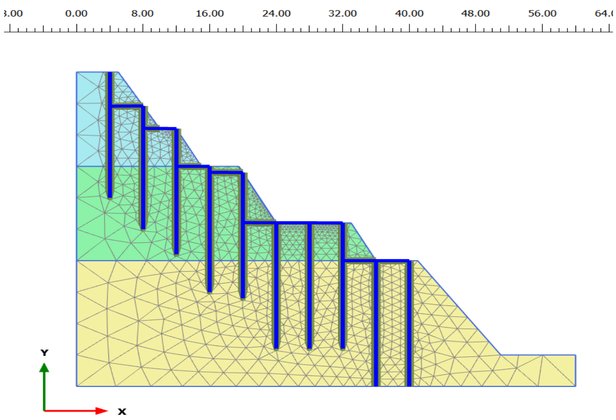

Figure 13: Slope model with hTP pile at every section

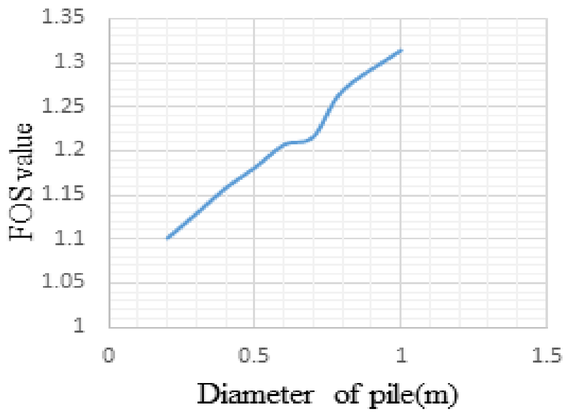

Figure 15: Factor of Safety vs Diameter of pile

3. Results and Discussion

FOS value of unreinforced slope is found to be 1.073, which is in marginally stable condition. Numerical models are computed by varying length, diameter and spacing of vertical piles. Maximum value of FOS is found to be 1.314 at the spacing 4m, diameter 1m and length 20m.**Figure 14** shows the deformed mesh of slope with vertical piles.

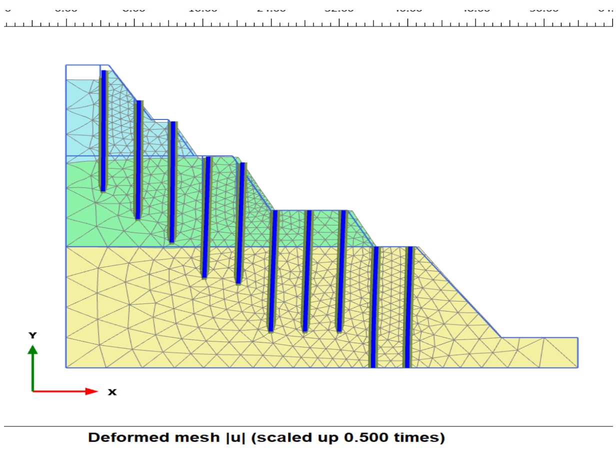

Figure 14: Deformed mesh of slope with vertical piles

3.1 Effect of diameter of pile

During numerical analysis, the diameter of pile is varied from 0.2m to 1m keeping other parameters constant i.e. spacing 4m and length 20m. It is found that factor of safety increases with increase in size of piles.

3.2 Effect of length of pile

During numerical analysis the length of pile is varied from 16m to 22m keeping other parameters constant i.e. diameter 1m and spacing 4m. Factor of safety increases up to 20m and then decreases.The deflection and bending moment of pile increases with increase in length of pile which contributes to the reduction in Factor of Safety after certain critical length.

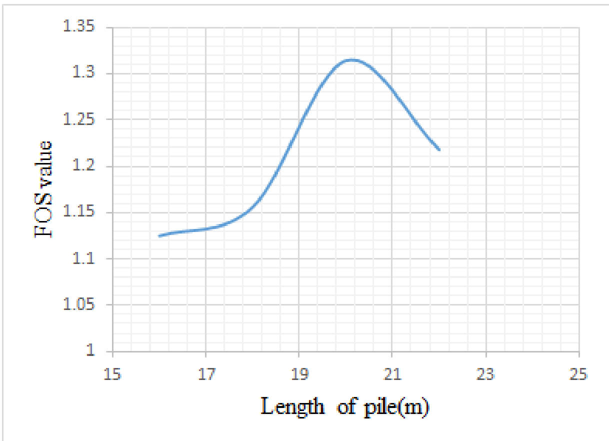

Figure 16: Factor of Safety vs Length of pile

3.3 Effect of spacing

During numerical analysis the spacing between piles is varied from 4m to 10m keeping other parameters constant i.e. diameter 1m and length 20m. It is found that factor of safety decrease with increase in spacing between piles.

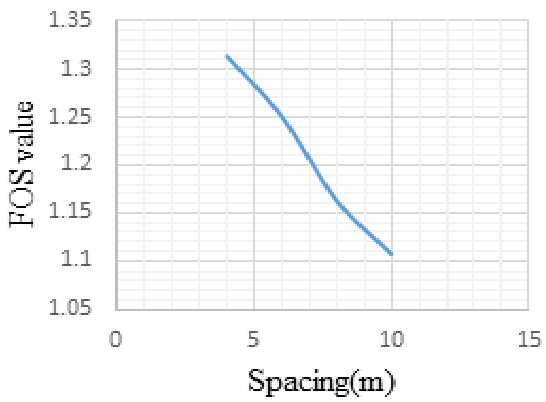

Figure 17: Factor of Safety vs Spacing of piles

3.4 h type anti-slide (hTP)pile

Numerical analysis of piled slope is carried out with spacing 4m, diameter 1m and length 20m by installing hTP pile at different location from top to bottom. Factor of Safety with hTP piles are found to have higher value than with only vertical piles i.e. 1.314. Maximum factor of safety is found to be 1.661 when hTP piles are installed at top and middle of the slope. Factor of safety values for different location of hTP is shown in **Table 4**.

Table 4: Factor of safety values for different location of hTP

Location of hTP pile	FOS value
Top	1.444
Middle	1.501
Bottom	1.386
Top and Middle	1.661
Top and Bottom	1.455
Middle and Bottom	1.592
Every section	1.581

4. Conclusion

From the finite element analysis of the piled slope models, based on the factor of safety values, some important conclusions drawn on the basis of the results are as follows:

1. Factor of Safety increase with increase in diameter of piles and decrease with increase in spacing between piles.
2. Factor of Safety increases with increase in length of pile and tends to decrease when the length of pile exceeds the critical length.
3. h type anti-slide (hTP) piles have better performance than only vertical piles in slope stabilization.
4. hTP piles are most effective when placed at the top and middle of the slope because Factor of Safety is found to be maximum as compared to other locations.

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